

On the Lack of X-ray Bright Type IIP Supernovae

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ABSTRACT

Type IIP Supernovae (SNe) are expected to arise from Red Supergiant stars (RSGs). These stars have observed mass-loss rates that span more than two orders of magnitude, from $< 10^{-6} M_{\odot} \text{ yr}^{-1}$ to almost $10^{-4} M_{\odot} \text{ yr}^{-1}$. Thermal bremsstrahlung X-ray emission from at least some IIP's should reflect the larger end of the high mass-loss rates. Strangely, no IIP SNe are seen where the X-ray luminosity is large enough to suggest mass-loss rates greater than about $10^{-5} M_{\odot} \text{ yr}^{-1}$. We investigate if this could be due to absorption of the X-ray emission. After carefully studying all the various aspects, we conclude that absorption would not be large enough to prevent us from having detected X-ray emission from high mass-loss rate IIP's. This leads us to the conclusion that there may be an upper limit of $\sim 10^{-5} M_{\odot} \text{ yr}^{-1}$ to the mass-loss rate of Type IIP progenitors, and therefore to the luminosity of RSGs that explode to form Type IIPs. This in turn suggests an upper limit of $\lesssim 19 M_{\odot}$ for the progenitor mass of a Type IIP SN. This limit is close to that obtained by direct detection of IIP progenitors, as well as that suggested by recent stellar evolution calculations. Although the statistics need to be improved, many current indicators support the notion that RSGs above $\sim 19 M_{\odot}$ do not explode to form Type IIP SNe.

Key words: Shock waves; circumstellar matter; stars: massive; supernovae: general; stars: winds, outflows; X-rays: ISM

1 INTRODUCTION

It is generally assumed that supernovae (SNe) evolve in the circumstellar wind medium carved out by their progenitor stars (Chevalier 1982a). The resulting emission from SNe, especially in the radio and X-ray, is due to the interaction of the SN shock wave with this circumstellar medium (Chevalier 1982b). The magnitude of the emission, especially the thermal X-ray emission, is a function of the circumstellar medium (CSM) parameters, in particular the density profile and structure of the circumstellar medium. This can be used to our advantage, so that the X-ray light curves of SNe can be used to uncover the density profile of the CSM (see for example Dwarkadas et al. 2010).

Stellar evolution theory posits that Type IIP SNe arise from Red Supergiant progenitors (Schaller et al. 1992; Langer 1993; Maeder & Meynet 2000; Langer 2012), which have low velocity winds of order 10 km s^{-1} , with mass-loss rates that span from 10^{-6} to $10^{-4} M_{\odot} \text{ yr}^{-1}$. All clearly identified progenitors of Type IIP SNe appear to be RSGs (Smartt 2009). Due to their low velocities and high mass-loss rates, the wind densities ($\rho_w \propto \dot{M}/(4\pi r^2 v_w)$) around RSG stars are expected to be some of the highest around SN progenitor stars. In particular the wind densities around Type

IIP SNe are expected to be much higher than those around Type Ib/c SNe, whose progenitors, thought to be Wolf-Rayet (W-R) stars, have much higher wind velocities, of order 1000 km s^{-1} , and thus wind densities that are proportionally lower. Thermal bremsstrahlung X-ray emission from SNe, due to circumstellar interaction (Chevalier 1982b), is proportional to the density squared. Consequently, if the X-ray emission is due to thermal bremsstrahlung, Type IIP SNe as a group would be expected to have some of the highest x-ray luminosities. The observations however indicate exactly the opposite, with IIP's having the lowest X-ray luminosities of all observed SNe (Figure 1).

The goal of this paper is to investigate the lack of X-ray bright Type IIP SNe, probe whether this is a real problem in the first place, and if so study the implications of this fact. In §2 we discuss the observed wind parameters of RSG stars. §3 displays the observed X-ray lightcurves of young SNe. §4 investigates whether absorption of the X-ray emission would prevent us from detecting type IIP SNe with high mass-loss rates. §5 discusses the implications of the results, and suggests that there may be a maximum mass above which RSGs do not explode to form IIP's. §6 summarizes the research and elucidates the important conclusions.

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2 RSG MASS-LOSS PARAMETERS

Several empirical prescriptions have been proposed in the literature to express the RSG mass-loss rate as a function of the stellar parameters (Reimers 1975; de Jager et al. 1988; Nieuwenhuijzen & de Jager 1990; Vanbeveren et al. 1998; Salasnich et al. 1999; van Loon et al. 2005). While they vary somewhat in their precise formulation, they all indicate that the mass-loss rate is proportional to some power of the RSG luminosity, with more luminous RSGs having higher mass-loss rates. Since the luminosity of the star increases with increasing stellar mass, it is clear that the mass-loss rate increases with increasing mass.

Mauron & Josselin (2011) have compared the mass-loss rate prescriptions with observationally calculated mass-loss rates of RSGs. Of the 8 RSGs which have a mass-loss rate measured from circumstellar gas observations, 3 have mass-loss rates greater than $10^{-5} M_{\odot} \text{ yr}^{-1}$, with at least one of these (depending on what measurement method is used) having a mass-loss rate greater than $10^{-4} M_{\odot} \text{ yr}^{-1}$. For another set of 39 RSGs, whose mass-loss rates were derived from the infrared excess at $60 \mu\text{m}$, 4 were found to have mass-loss rates higher than $10^{-5} M_{\odot} \text{ yr}^{-1}$. For RSGs in the LMC, there was considerably more scatter among different methods used to estimate the mass-loss rates, with the most conservative one (using *Spitzer* data), having mass loss rates generally below $10^{-5} M_{\odot} \text{ yr}^{-1}$ with one exception, whereas those using IRAS fluxes generally had mass-loss rates exceeding $10^{-5} M_{\odot} \text{ yr}^{-1}$.

The terminal velocities of RSG winds are hard to measure, but are low, and less than the escape velocities from the star. Although the velocities are generally taken to be around 10 km s^{-1} , there is some variation in the velocities. Josselin et al. (2000) suggest velocities of 25 km s^{-1} for M supergiants, following the observational work of Jura (1986) and Knapp & Morris (1985). Mauron & Josselin (2011) find velocities for RSG winds generally above 10 km s^{-1} , and stretching all the way up to 50 km s^{-1} . Furthermore, there is some indication of a variation with luminosity, and therefore with mass-loss rate, with those having higher mass-loss rates also having higher velocities, although this relationship isn't confirmed. Velocities for RSGs in the LMC follow the same trend, but appear to be about 30% lower.

There understandably exists considerable confusion over observed mass-loss parameters of RSGs, given the various measurement methods used, and the fact that RSG properties are difficult to measure. Nevertheless, there seems to be general agreement that there exist at least a few RSGs with *measured* mass-loss rates exceeding $10^{-5} M_{\odot} \text{ yr}^{-1}$. Humphreys (2007) mentions a few post-RSGs, or cool hypergiants, with mass-loss rates exceeding $10^{-4} M_{\odot} \text{ yr}^{-1}$, at least for short periods of time. *Theoretical considerations* imply that as the luminosity increases, the mass-loss rate should increase. RSGs with luminosities $> 3 \times 10^5 L_{\odot}$ are observed, corresponding to large progenitor masses and therefore larger mass-loss rates. It is then problematic that not a single Type IIP SN has been seen with a high X-ray luminosity (§3), indicating a mass-loss rate $> 10^{-5} M_{\odot} \text{ yr}^{-1}$. This cannot be purely a selection problem, since if the RSG winds are observable there is no reason why the brighter Type IIP SNe should not be observable.

3 X-RAY EMISSION FROM TYPE IIP SNE

Figure 1 shows the X-ray emission from young SNe, grouped by type. As can be seen, Type IIP SNe have the lowest levels of X-ray emission¹. Bremsstrahlung emission is proportional to the square of the density. If, in the simplest approximation, this plot is looked on as representative of the ambient density in which the SNe evolve, with X-ray emission due to thermal bremsstrahlung, then it would appear as if Type IIP's evolve in a medium with the lowest density, and Type IIs in media with the highest density. While it is very possible that many IIs evolve in media with very high densities, it seems strange that IIPs, at least a few of which should have very high density media around them, appear to have the lowest luminosities as a group.

Chevalier & Fransson (2003) give the free-free X-ray luminosity from the SN shocks:

$$L_x \approx 3. \times 10^{39} g_{ff} C_n \left(\frac{\dot{M}_{-5}}{v_{w1}} \right)^2 t_{10}^{-1} \quad (1)$$

where g_{ff} is the gaunt factor, of order unity, $C_n = 1$ for the circumstellar medium shock, and $C_n = (n-3)(n-4)^2/[4(n-2)]$ for the reverse shock, \dot{M}_{-5} is the mass loss rate in units of $10^{-5} M_{\odot} \text{ yr}^{-1}$, v_{w1} is the wind velocity in units of 10 km s^{-1} , and t_{10} is time in units of 10 days. This assumes electron-ion equilibration, and a freely-expanding wind with constant mass-loss parameters. It is clearly seen that, given the luminosities in Fig 1 all being below 3×10^{39} , all the observed X-ray epochs for type IIP SNe suggest mass-loss rates below $10^{-5} M_{\odot} \text{ yr}^{-1}$ for a wind velocity of 10 km s^{-1} , if the emission is due to thermal bremsstrahlung. If the wind velocity is a factor of 2-3 higher, then the mass-loss rate is correspondingly higher, and for the most luminous cases may exceed $\dot{M}_{-5} = 1$.

In Table 1 we show the mass-loss rates, and progenitor masses, of Type IIP SNe computed by various authors. These are calculated from radio, x-ray and optical data. We also show the corresponding calculated progenitor mass for the SN, which are calculated by a variety of means, including direct detection of progenitors in pre-explosion images (Smartt et al. 2009), spectroscopic modelling, and hydrodynamical modelling. The method is identified in column 4.

Data on some SNe in Table 1 is expanded over multiple rows, where multiple groups using different techniques calculated mass-loss rates or progenitor masses, using data over a multitude of wavelengths. In all but one case, the calculated mass-loss rate is lower than $10^{-5} M_{\odot} \text{ yr}^{-1}$. In many cases where a mass-loss rate is not specified, the inferred progenitor mass would suggest a mass-loss rate below $10^{-5} M_{\odot} \text{ yr}^{-1}$.

Progenitor masses calculated from hydrodynamical

¹ We note that 1994W was classified as Type IIP by Sollerman et al. (1998) following the photometry of Tsvetkov (1995). The high X-ray luminosity would have made it probably the brightest observed IIP in X-rays. However it has subsequently been cited as Type II by most authors. It is possible that it belongs to the group of SNe whose classification evolves with SN evolution. However its properties, and X-ray emission, appear to place it amongst the IIs. In this paper we have classified it as a II

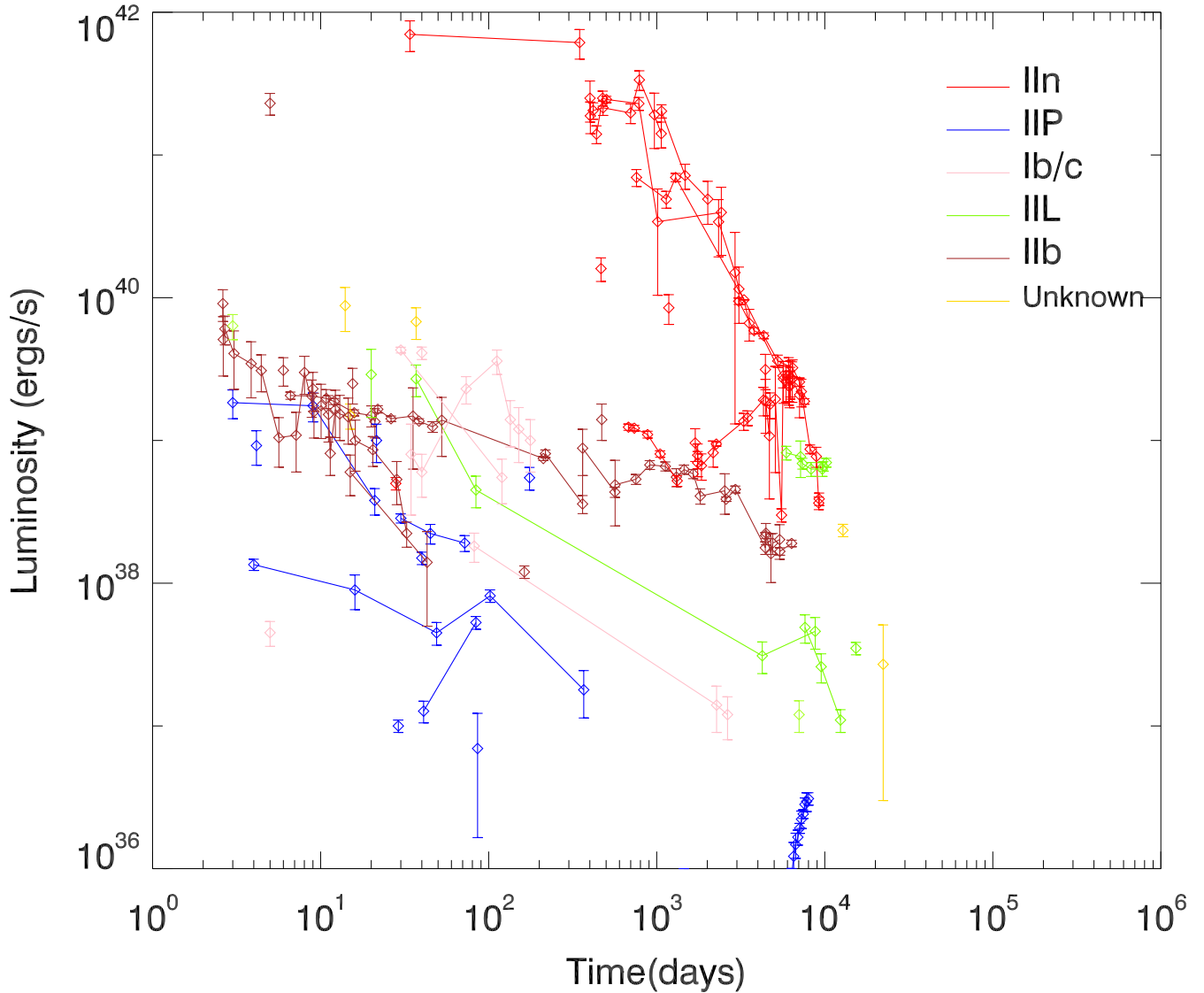


Figure 1. The light curves of most published SNe, by type. This figure is adapted from a similar figure first published in Dwarkadas & Gruszko (2012), with many more SNe added. It is clearly seen that the light curves of Type IIP SNe generally lie below a luminosity of 10^{39} ergs s^{-1} , almost three orders of magnitude below the brightest observed SNe. Note: GRB SNe are not included in this list.

modelling appear to be systematically higher than those calculated from the data, either spectra or light-curves. A major exception to the low mass-loss rate appears to be the ultraviolet-bright SN 2009kf (Botticella et al. 2010), whose early ultraviolet lightcurve appears to indicate either a very large energy and high-mass progenitor (Utrobin et al. 2010), or an exceptionally high mass-loss rate (Moriya et al. 2011).

4 SUGGESTED REASONS FOR THE LACK OF X-RAY BRIGHT IIP'S

As mentioned above, there are clear indications that RSGs with high mass-loss rates exist. These are expectedly fewer in number, consistent with a steep initial mass-function that

is strongly biased towards lower-mass stars. It is also clear that IIPs arise from RSGs. Almost all SNe whose progenitors are reasonably well confirmed appear to be Type IIP SNe, and their progenitors appear to be RSGs (Smartt 2009; Smartt et al. 2009). However none of the progenitors appear to have an initial mass exceeding $16.5 \pm 1.5 M_{\odot}$. The lack of high mass RSG progenitors of Type IIP SNe has been touched on by Smartt et al. (2009), who refer to it as the “red supergiant problem”.

4.1 Absorption of the X-ray Emission

The majority of observations of Type IIP SNe in X-rays (1) appear to be at an age of < 100 days. Chevalier et al.

Table 1. The progenitor masses, and mass-loss rates, deduced for Type IIP SNe in the literature. References: (1) Chevalier et al. (2006, and references within) (2) Roy et al. (2011) (3) Utrobin et al. (2010) (4) Moriya et al. (2011) (5) Misra et al. (2007) (6) Jerkstrand et al. (2012) (7) Chakraborti et al. (2012) (8) Chakraborti et al. (2013) (9) Moriya et al. (2012) (10) Tomasella et al. (2013) (11) Utrobin & Chugai (2013) (12) Utrobin & Chugai (2008) (13) Utrobin & Chugai (2009) (14) Utrobin et al. (2007) (15) Utrobin & Chugai (2011) (16) Bose et al. (2013) (17) Inserra et al. (2012) (18) Inserra et al. (2011) (19) Van Dyk et al. (2012) (20) Maund et al. (2013) (21) Maund et al. (2014) (22) Maund et al. (2014) (23) Smartt et al. (2009) (24) Van Dyk et al. (2012)

SN	Progenitor Mass (M_{\odot})	Mass-Loss Rate ($10^{-6} M_{\odot} \text{ yr}^{-1}$)	Mass (or Mass-loss Rate) Method	Reference
1999an	< 18	...	Optical progenitor identification	23
1999br	< 15	...	Optical progenitor identification	23
1999em	< 15	5	radio synchrotron; Optical progenitor identification	1, 23
1999ev	16_{-4}^{+6}	...	Optical progenitor identification	23
1999gi	< 14	...	Optical progenitor identification	23
2000cb	26.3 ± 2	...	Hydrodynamic model	15
2001du	< 15	...	Optical progenitor identification	23
2002hh	< 18	7	radio synchrotron; Optical progenitor identification	1, 23
2003gd	8.4 ± 2	...	Optical progenitor identification	21
2003gd	7_{-2}^{+6}	...	Optical progenitor identification	23
2003ie	< 25	...	Optical progenitor identification	23
2003Z	14.4 -17.4	< 0.16	Hydrodynamic model	14
2004A	12 ± 2.1	...	Optical progenitor identification	21
2004A	7_{-2}^{+6}	...	Optical progenitor identification	23
2004am	12_{-3}^{+7}	...	Optical progenitor identification	23
2004dg	< 12	...	Optical progenitor identification	23
2004dj	$15, \sim 12$	2-3	radio synchrotron	1
2004dj	15	0.32 ± 0.11	X-ray, radio; observations and theory	7
2004dj	15 ± 3	...	Optical progenitor identification	23
2004et	15_{-2}^{+5}	9-10	radio synchrotron	1
2004et	~ 20	~ 2	X-ray luminosity	5
2004et	27 ± 2	...	Hydrodynamic model	13
2004et	< 15	...	Late-time spectral modelling	6
2004et	9_{-1}^{+5}	...	Optical - direct progenitor identification	23
2005cs	18.2 ± 1	...	Hydrodynamic model	12
2005cs	$9.5_{-2.2}^{+3.4}$...	Optical progenitor identification	21
2005cs	7_{-1}^{+3}	...	Optical progenitor identification	23
2006bc	< 12	...	Optical progenitor identification	23
2006my	9.8 ± 1.7	...	Optical progenitor identification	21
2006my	< 13	...	Optical progenitor identification	23
2006ov	< 10	...	Optical progenitor identification	23
2007aa	< 12	...	Optical progenitor identification	23
2007od	9.7-11	...	Modelling bolometric light curve	18
2008bk	8-8.5	...	Evolutionary Models	19
2008bk	12.9 ± 1.7	...	Optical progenitor identification	22
2008bk	9_{-1}^{+4}	...	Optical progenitor identification	23
2008in	< 20; 15.5 ± 2.2	< 5	Hydrodynamical model	2, 11
2009bw	11-15	~ 1 (< 100)	Modelling light curve	17
2009kf	~ 36	< 90	Hydrodynamic Modelling	3
2009kf	...	> 100, 10000	radiation hydrodynamics	4, 9
2011ja	> 16	0.27 ± 0.05 ; 7.5 ± 1.5	X-ray, radio fitting	8
2012A	10-15	...	Optical progenitor; Hydrodynamic Modelling	10
2012aw	14-15	...	Observations; Hydrodynamical Modelling	16
2012aw	15-20	...	Evolutionary tracks	24
2012ec	14-22	...	Optical - photometric and Spectroscopic	20

(2006) suggest that the early emission from Type IIP SNe may be due to inverse Compton scattering of the photospheric photons. However, if the mass-loss rate of the RSG were higher, thermal bremsstrahlung would be expected to dominate. Chevalier et al. (2006) also suggest that emission from the reverse shock would dominate, unless the reverse shock were to be radiative. For mass-loss rates $> 10^{-5} M_{\odot} \text{ yr}^{-1}$, and an age < 100 days, the reverse shock in IIP's is expected to be radiative (Fransson et al. 1996; Chevalier et al. 2006), and a cool shell is expected to form that will absorb

almost all the emission from the reverse shock. Thus for higher mass-loss rates, one would expect the emission to arise from the forward shocked circumstellar wind material in Type IIP SNe.

We explore if emission from the circumstellar shock in high luminosity IIPs could be absorbed by the forward-shocked material, as has been suggested by some authors (Moriya et al. 2012). The velocity of the forward shock can be written as (Chevalier et al. 2006):

$$V_f = 1.6 \times 10^4 \left[\frac{\dot{M}_{-6}}{v_{w1}} \right]^{-0.1} E_{51}^{0.45} \left[\frac{M_{ej}}{10 M_\odot} \right]^{-0.345} \times \left[\frac{t}{10 \text{ days}} \right]^{-0.10} \text{ km s}^{-1} \quad (2)$$

where $v_{w,1}$ is the wind velocity in units of 10 km s^{-1} , and \dot{M}_{-6} is the wind mass-loss rate in units of $10^{-6} M_\odot \text{ yr}^{-1}$. This is for a specific value of the ejecta density profile $n = 11.73$, and will vary slightly for different profiles. Note that the variation of the forward shock velocity with mass-loss rate (assuming a constant wind velocity) is small - modifying the mass-loss rate by a factor of 100 decreases the forward shock velocity to 0.63 times its original value. This equation can be used to approximate the velocity evolution.

Since the ionization structure of the ambient medium plays a significant role in determining the photo-electric absorption, the ionization structure of the surrounding wind material needs to be investigated. We first consider the ionization from the SN explosion and resulting UV flash. For a medium consisting of pure H, Lundqvist & Fransson (1996) estimate that the burst can ionize anywhere from 0.5 to $2 M_\odot$ of material. Although these models are for Blue (and not Red) supergiant progenitors, they provide an approximate estimate that the SN explosion should ionize around $0.5 M_\odot$. This will then ionize the RSG wind out to a radius R_i where

$$R_i = 1.6 \times 10^{19} M_{i,0.5} v_{w,1} \dot{M}_{-6}^{-1} \text{ cm} \quad (3)$$

where $M_{i,0.5}$ is the total mass that can be fully ionized by the explosion, in units of $0.5 M_\odot$. It can be seen that even for mass-loss rates $\sim 10^{-4} M_\odot \text{ yr}^{-1}$, the wind material can be ionized out to 10^{17} cm .

However the densities close to the star are extremely high, and recombination proceeds rapidly. The recombination time can be estimated as

$$t_{rec} \sim \frac{3 \times 10^{12}}{n_e} \sim 1.2 \times 10^6 r_{15}^2 v_{w,1} \dot{M}_{-6}^{-1} \text{ s} \quad (4)$$

where r_{15} is the radius in units of 10^{15} cm .

Using equations 2 and 4 suggests that for $\dot{M}_{-6} = 1$, the recombination time will be larger than the SN age after about 30 days. Therefore the wind from that radius out should be ionized, and optically thin to the thermal X-ray flux.

This is consistent with observational data. Misra et al. (2007) find the mass-loss rate for SN 2004et to be $\dot{M}_{-6} \lesssim 2$ from the X-ray data. For 3 *Chandra* observations, taken at 30, 45 and 72 days after explosion, the column density is consistent with the Galactic value, with no additional column around the star, suggesting the presence of an ionized wind that does not add to the absorption. Our own analysis of the data finds results consistent with the fluxes obtained by Misra et al. (2007) within the error bars. We also find that if we set the minimum column to be the Galactic value (Dickey & Lockman 1990; Kalberla et al. 2005), the best fit to the spectrum is always obtained at this minimum value.

For higher mass-loss rates, the recombination time decreases appropriately. For $\dot{M}_{-6} = 10$, the recombination time is smaller than the SN shock flow time for about 5

months, whereas for $\dot{M}_{-6} = 100$, the recombination time is less than the SN shock travel time for about 4 years. We can consider that for all the early observations, at mass-loss rates $> \dot{M}_{-6} = 10$, the medium no longer shows the effects of the initial ionizing radiation.

However, the X-ray emission itself can photo-ionize the medium. The importance of this mechanism depends on the value of the ionization parameter $\chi = L_x/(n r^2)$ (Kallman & McCray 1982). Assuming the X-ray luminosity to be given by equation 1, we can write

$$\chi = 120 \dot{M}_{-5} v_{w1}^{-1} t_{10 \text{ days}}^{-1} \quad (5)$$

Chevalier & Irwin (2012) have studied the effects of χ on the ionization. For $\chi \gtrsim 100$, the elements C, N, O are completely ionized; however ionization of the heavier elements requires $\chi \gtrsim 1000$. The results are also somewhat dependent on the temperature of the radiation field. For $\dot{M}_{-5} \sim 10$ most of the elements will be highly ionized, and the medium may be considered mostly ionized in the first couple of weeks. By about 100 days though the heavier elements will not be fully ionized, and thus some absorption by Si and Fe could be expected. For $\dot{M}_{-5} \sim 1$, C, N and O are ionized in the first few days, but only low ionization stages are present after the first few weeks.

Unless the medium is fully ionized, which is true only during the first couple of weeks for the largest mass-loss rates considered here, some absorption of the X-ray emission is expected. Although it would require a time-dependent ionization calculation to compute accurately, some estimates can be made. In the wavelength range between 0.2-4 KeV, where we expect much of the X-ray absorption to take place, the most important contributions to the opacity arise from K-shell absorption by carbon, nitrogen and oxygen. Fransson (1982) estimates the optical depth at an energy E to be

$$\tau(E) \sim 43 \dot{M}_{-4} v_{w,6}^{-1} r_{15}^{-1} E_{keV}^{-8/3} \quad (6)$$

Fransson (1982) indicates that the expression is correct to within a factor of two independent of the ionization state, as long as the atoms are not completely stripped of electrons, i.e. that the medium is not totally ionized.

In the first 10 days we would not expect the SN shock to have travelled more than 10^{15} cm , and in the first 100 days one would expect the shock radius to be around 10^{16} cm . Thus, from equation 6, for all mass-loss rates $\gtrsim 2 \times 10^{-6} M_\odot \text{ yr}^{-1}$, the optical depth at 1 keV will be larger than 1. For a velocity of 10^4 km s^{-1} , we find that the distance traveled in one month will be $2.6 \times 10^{15} \text{ cm}$. For a mass-loss rate of $\dot{M}_{-5} \sim 1$, and a somewhat higher wind velocity of 20 km s^{-1} (see §2), the optical depth has dropped below unity already, and continues to fall as the SN shock expands outwards. Thus at times later than about a month after explosion, and for a mass-loss rate around $10^{-5} M_\odot \text{ yr}^{-1}$, we would expect that while there is some absorption, the total flux is large enough to be observable. At higher mass-loss rates, while the optical depth is still high, note that the luminosity is increasing as the square of the mass-loss rate. Thus for a mass-loss rate of $\dot{M}_{-5} = 5$ and wind velocity 20 km s^{-1} , we find that the luminosity increases by over a factor of 6 compared to the previous case. At about 30 days, the optical depth is around 4, but the total flux, for a SN at 10 Mpc,

is about 3×10^{-14} ergs $\text{s}^{-1} \text{cm}^{-2}$, using equation 1. This is about half that noted for the last 2004et observation, and detectable. At later times the luminosity decreases but the optical depth also decreases.

At the highest RSG mass-loss rates of $10^{-4} M_{\odot} \text{yr}^{-1}$, the medium can be considered totally ionized for the first two weeks due to photo-ionization from the shock. Subsequently, for the first 100 days C, N, and O will still be almost fully ionized, although heavier species will not, and some absorption will undoubtedly occur. But following the argument above, particularly if the wind velocity exceeds 30 km s^{-1} at the highest mass-loss rates as observations suggest, the optical depth will exceed unity, but the X-ray flux for a SN within 10 Mpc will be in the range of a few times $10^{-14} \text{ ergs s}^{-1} \text{cm}^{-2}$. Furthermore, assuming that C, N and O are fully ionized will reduce the photo-absorption and the optical depth to values below that quoted above, and thus increase the observed flux.

We can examine this from another perspective. Many of the type IIP SNe that are seen have their X-ray luminosity, at least early on, dominated by IC processes, which exceeds the thermal bremsstrahlung. However, other SN types with mass-loss rates around $10^{-5} M_{\odot} \text{yr}^{-1}$ or somewhat less are clearly seen (Figure 1), so there should be no reason for IIPs with similar mass-loss rates to go undetected. Furthermore, as the emission goes as density squared, the luminosity will increase by a factor of 100 for an increase of a factor of 10 in mass-loss (equation 1). If the luminosity is 100 times higher for the highest mass-loss rate ones, even an optical depth of 4 will return about the same flux as the lower mass-loss rate SN (assuming the same distance of course) and thus should be detectable. Therefore, given that other SNe are detectable, and thermal emission from some low density type IIPs is seen, it becomes hard to justify that not a single high mass-loss rate one has been detected.

If all the emission were to fall in the *Chandra* or *XMM* band, it would be detectable with a 50 ks observation. Next we investigate what fraction of the emission from the forward shock would fall in the 0.5-10 keV range over which current X-ray satellites work. For a shock velocity 10^4 km s^{-1} , the post-shock temperature will be about 10^9 K . If we assume that electrons are heated purely by Coulomb collisions, the time taken for electrons and ions to reach temperature equilibrium is:

$$t_{eq} = 5 \times 10^5 \frac{T_{e9}^{3/2}}{n_{e9}} \text{ s} \quad (7)$$

where T_{e9} is the electron temperature in units of 10^9 K , and n_{e9} is the electron density in units of 10^9 cm^{-3} . Given that

$$n_{e9} = 0.1 \dot{M}_{-5} v_{w,1}^{-1} r_{15}^{-2} \quad (8)$$

we have

$$t_{eq} = 5 \times 10^6 T_{e9}^{3/2} \dot{M}_{-5}^{-1} v_{w,1}^2 r_{15}^2 \text{ s} \quad (9)$$

Therefore, except at the highest mass-loss rates ($> 10^{-4} M_{\odot} \text{yr}^{-1}$), and large SN velocities, i.e in the first couple of weeks, the equilibration time is larger than the age of the SN. Thus the electrons will not in general attain temperature equilibrium with the ions, and the electron temperature will be

lower than the ion temperature. Collisionless plasma processes may play a role, but at these high densities will not be expected to dominate. This is consistent with the results of Chevalier & Irwin (2012) as expressed in their Figure 1.

In equation (1) we assumed that the luminosity was due to electron-ion equilibration. If this is not achieved, as outlined above, and the electron temperature is lower than the post-shock temperature, what fraction of the flux falls into the *Chandra* 1-10 keV band? This depends on many factors such as the ratio of electron-ion temperature, steepness of the ejecta density profile, and density of the medium, and requires a detailed exploration of the parameter space. However, the basic idea has been summarized in the calculations by Fransson et al. (1996) (see their figures 8 and 10). The X-ray flux in the 1-10 keV band in their calculations for SN 1993J, with mass-loss rates comparable to those we are assuming here, is a factor of 5-10 lower than the total X-ray flux. Note that these calculations assume that $T_e = T_{coul}$, and it is possible that plasma processes could make the electron temperature greater than the Coulomb temperature (although still lower than the ion temperature). Given the flux that we computed earlier, a factor of a few lower in the first 100 days makes the SN harder to detect, but it is still detectable with long exposures of 50-100 ks. As expected, over time the post-shock temperature decreases and more and more of the X-ray flux falls into the *Chandra* and *XMM* bands. After a few hundred days or so, most of the flux from the SN shock lies in the 1-10 keV band.

So far we have considered the emission mainly within 100 days after explosion. As is evident from the above discussion, while the luminosity will be decreasing with time, the temperature will also be decreasing, thus moving a larger fraction of the emitted flux into the *Chandra* wavebands. The medium further out will have a much lower opacity, and thus most of the X-ray emission will manage to escape unabsorbed. Therefore at later times (several months to a year) it should also be possible to detect X-ray emission from high mass-loss rate Type IIPs.

Furthermore, as the SN shock advances in radius, and the density in the wind decreases, the reverse shock will no longer be radiative, a dense shell will not form that absorbs most of the reverse-shocked emission, and the X-ray emission from the reverse shock will begin to contribute. After a 100 days, the column density behind the reverse shock, for a mass-loss rate of $> 10^{-5} M_{\odot} \text{yr}^{-1}$, is a few times 10^{21} cm^{-2} (Chevalier et al. 2006). Thus most of the emission below 1 keV will be absorbed, but we would still expect emission $> 1 \text{ keV}$ to be visible.

It could be argued that late-time X-ray emission from a IIP SN would not be detected, because there would be no reason to observe the SN if early-time emission was not detected. While this is true, it does not preclude the fact that the SN could be detected serendipitously while observing the galaxy, or via Sky Surveys. One such is the XMM Serendipitous Source Catalogue, the third release of which was in July 2013. This lists sources found by XMM during their sky survey. The median flux of all sources is $2 \times 10^{-14} \text{ erg cm}^2 \text{s}^{-1}$. We have looked through the list, and notably, we have not found a single late time Type IIP SN seen, as would be expected if such high density media were present around them. We note that there are many Chandra observations of galaxies covering the region where optical Type

IIP SNe are present, and again there is no recorded late time detection of optically observed Type IIPs.

From multiple arguments, it seems likely that at epochs > 100 days, if high mass-loss rate Type IIPs were to exist, they should have been detected.

One final aspect that needs to be taken into account is Comptonization of the high energy electrons (Chevalier & Irwin 2012; Pan et al. 2013). Comptonization limits the maximum energy of escaping photons to $E_{max} \sim 511/\tau_{es}^2$, where τ_{es} is the electron scattering optical depth. We note that this affects the flux in the *Chandra* band only when $\tau_{es} \gtrsim 8$. If we assume that $\tau_{es} \leq \tau_E$ as expected, then Comptonization is not important for our results.

In summary, we can say that it is unlikely that the X-ray emission from IIPs with higher mass-loss rates would be absorbed so much as not to have been detected by current X-ray satellites. Thus absorption of the X-ray emission cannot be used to cover the fact that no X-ray bright Type IIP SNe are seen.

5 DISCUSSION

The two main results from the above sections are that (1) RSGs with high mass-loss rates ($> 10^{-5} M_{\odot} \text{ yr}^{-1}$) certainly exist in our galaxy and in other nearby galaxies, and (2) if Type IIP SNe were to explode in a medium formed by RSGs with these high density winds, then they should be detectable.

This presents a quandary. If Type IIP SNe arise from RSG stars, it is surprising that only Type IIP SNe from low mass-loss rate RSG stars are seen. In the absence of other explanations, one is left with the conclusion that IIPs arise only from those RSGs that have a low mass-loss rate. Since mass-loss rate is directly related to the initial progenitor mass, this would then suggest that IIPs arise only from the lower end of the RSG mass distribution.

We can compute the upper limit based on current observational constraints. Figure 1, combined with equation 1 and Table 1, suggests a maximum mass-loss rate of $10^{-5} M_{\odot} \text{ yr}^{-1}$ for the ambient medium around Type IIPs. Although this refers specifically to the mass-loss rate measured towards the end of the RSG lifetime, we assume that the mass-loss rate is constant throughout the RSG lifetime. Various prescriptions of mass-loss differ somewhat, however a mass-loss rate of $10^{-5} M_{\odot} \text{ yr}^{-1}$ corresponds to a RSG luminosity of about $0.5\text{--}2 \times 10^5 L_{\odot}$ (Mauron & Josselin 2011). The Geneva mass-loss rate quoted by Mauron & Josselin (2011)

$$\dot{M} = 4.7 \times 10^{-6} (L/10^5)^{1.7}$$

gives a luminosity around $1.6 \times 10^5 L_{\odot}$. If we use this value, and the relationship between mass and luminosity suggested by Mauron & Josselin (2011)

$$M \sim 0.14 L^{0.41}$$

where mass M and luminosity L are both in terms of solar values, then we get a mass of $M \sim 19 M_{\odot}$ as the maximum mass of the RSG progenitor of a Type IIP SN. In actual fact most mass-loss rates are lower, so the value could be somewhat lower.

Amazingly, given the uncertainties, this value is close to others that have been quoted in the literature. In their

paper describing the RSG problem, Smartt et al. (2009) suggest that the maximum mass of a RSG progenitor that can give rise to a Type IIP SN is $16.5 \pm 1.5 M_{\odot}$. This is an observational limit derived from the progenitors of Type IIP SNe that have been carefully identified in pre-explosion images, with a significance of about 2.4σ . On the other hand, recent theoretical work (Georgy et al. 2012; Groh et al. 2013; Georgy et al. 2013) suggests that rotation restricts the maximum mass of RSGs that explode to give Type IIP SNe to about $16.8 M_{\odot}$; RSGs larger than this evolve to become nitrogen-rich (WN) stars before they explode, resulting presumably in Ib/c SNe. Non-rotating RSGs that become Type IIP SNe are also limited to an initial mass of $19 M_{\odot}$ due to increased mass-loss. These stars will not end their lives to produce Type IIP SNe.

It is interesting that the maximum mass of Type IIP SNe progenitors, obtained from mass-loss rate limits calculated from X-ray observations, agree quite well with those obtained by other means. We must caution however that none of the observational methods are entirely convincing due to low statistics. In this context it is interesting to look at the progenitor masses deduced for various Type IIPs as in Table 1. Those which have mass-loss rates determined all (except one) fall below the $19 M_{\odot}$ limit calculated herein. This is not surprising, as the initial progenitor mass, notwithstanding how it is computed, is somehow related to the derived mass-loss rate, and therefore would be expected to give a lower initial mass progenitor. Recently, approaches involving the modelling of late-time spectra (Jerkstrand et al. 2012) also appear to find masses at the lower end of the RSG mass range, consistent with those from direct detection of progenitors. These are however in direct contrast to masses derived from hydrodynamic modelling (Utrobin et al. 2007; Utrobin & Chugai 2008, 2009; Utrobin et al. 2010; Utrobin & Chugai 2011, 2013), which tend to be consistently higher. Although the reasons for this are not known, some that have been speculated are the neglect of multi-dimensional effects, explosion asymmetries, and the use of non-evolutionary models in hydrodynamic modelling. This is not a problem relegated to one particular code or group either; Tomasella et al. (2013) found that their best estimate of the progenitor mass of SN 2012A from their hydrodynamic modelling was 30% higher than that from direct mass estimates. It is important that the results for this discrepancy be understood and evaluated in future, because the hydrodynamical masses seem to consistently exceed the upper mass-limit found from other means.

An exception to all the other Type IIP SNe is SN 2009kf, whose progenitor mass calculated from hydrodynamical modelling ($36 M_{\odot}$) is larger than the maximum mass of stars known to end their lives in the RSG phase. Although by its light curve it resembles Type IIP, the explosion energy requirements ($\gtrsim 10^{52}$ ergs) suggest that it is different from most (all?) other IIPs. The large explosion energy required to explain its light curve prompted Utrobin et al. (2010) to suggest that SN 2009kf was caused by the same “engine” that leads to the so-called hypernova explosions. They further speculate that binary evolution of two massive stars could result in a SN 2009kf type scenario. Piro & Ott (2011) explore fallback accretion onto newly-born magnetars, and find that for stars with a $> 10 M_{\odot}$ H envelope, this would give a bright Type IIP SNe with a high plateau luminosity.

In any realistic scenario, it is clear that SN 2009kf differs from others in the IIP category. This does not necessarily contradict the mass-limit found above. It may simply be an artifact of an inadequate classification scheme that classifies SNe based on one particular aspect of their light curve, and expects all SNe that show similar light curves (in that one aspect) to have similar progenitors. The lack of a single progenitor for a similar group of SNe has been mentioned in the context of Type IIn SNe, which show narrow lines on top of a broad base in their spectra. For many years IIns were thought to arise from high-mass progenitors, but studies of their host environments do not seem to confirm this hypothesis (Anderson & James 2008; Kelly & Kirshner 2012). There seem to be several indirect indications that multiple progenitor channels may be involved (Dwarkadas 2011; Taddia et al. 2013)

6 SUMMARY AND CONCLUSIONS

If the X-ray emission from young SNe arises due to thermal bremsstrahlung, then it should be a strong function of the ambient density. If we group the light curves by type of SN, those interacting with the higher density material should have higher luminosities. In this context it is unusual that a plot of X-ray lightcurves shows that Type IIP SNe have the lowest X-ray luminosities. This is counter-intuitive given that IIPs are supposed to arise from RSGs, which have slow, high mass-loss rate winds and are therefore expected to have a high-density medium around them. Indeed, measurements of the medium around some RSGs do suggest that they have wind mass-loss rates in excess of $10^{-5} M_{\odot} \text{ yr}^{-1}$. However these are not reflected in the X-ray lightcurves of the corresponding Type IIP SNe.

In this paper we have examined the reasons for this. It is unlikely that IIPs do not arise from RSGs; a large envelope is required to explain the plateau in the light curve. We have examined whether the X-ray flux from high mass-loss rate IIPs could be absorbed by the surrounding medium. Although this is a complicated question that requires investigating several different aspects, the conclusion seems to be that we should have seen at least some type IIPs exploding in a higher density medium, either at early (first 100 days) or late times. The fact that we have not seen any suggests that maybe Type IIPs do not explode in a high mass-loss rate medium ($> 10^{-5} M_{\odot} \text{ yr}^{-1}$). If this is true, then it implies a limit of below $19 M_{\odot}$ for the initial mass of a Type IIP progenitor. This is close to the numbers quoted by direct detection of IIP progenitors, as well as recent theoretical arguments. This would require changes in the way we view the evolution of RSG stars with initial masses between about ~ 19 - $25 M_{\odot}$.

Further statistics are required before these claims can be solidified. Even a single solid detection of a Type IIP with a luminosity exceeding about $10^{40} \text{ ergs s}^{-1}$ would create problems for this assertion. Till then, it appears that different indicators appear to converge on the suggestion that not all RSGs give rise to Type IIP SNe, but that those with initial mass $> 17 - 19 M_{\odot}$ may evolve to some other type of star before explosion, perhaps the WN stars. Observations of more IIPs in the X-ray regime would certainly help to solidify this claim from the X-ray point of view.

ACKNOWLEDGMENTS

VVD's research is supported by several Chandra grants. We thank the anonymous referee for comments that helped to considerably improve the paper, and R. Chevalier for extremely helpful comments on an earlier version of this manuscript.

REFERENCES

- Anderson J. P., James P. A., 2008, MNRAS, 390, 1527
- Bose S., Kumar B., Sutaria F., Kumar B., Roy R., Bhatt V. K., Pandey S. B., Chandola H. C., Sagar R., Misra K., Chakraborti S., 2013, MNRAS, 433, 1871
- Botticella M. T., Trundle C., Pastorello A., Rodney S., Rest A., Gezari S., Smartt S. J., Narayan G., Huber M. E., Tonry J. L., Young D., Smith K., Bresolin F. e. a., 2010, ApJL, 717, L52
- Chakraborti S., Ray A., Smith R., Ryder S., Yadav N., Sutaria F., Dwarkadas V. V., Chandra P., Pooley D., Roy R., 2013, ArXiv e-prints
- Chakraborti S., Yadav N., Ray A., Smith R., Chandra P., Pooley D., 2012, ApJ, 761, 100
- Chevalier R. A., 1982a, ApJ, 258, 790
- Chevalier R. A., 1982b, ApJ, 259, 302
- Chevalier R. A., Fransson C., 2003, in Weiler K., ed., Supernovae and Gamma-Ray Bursters Vol. 598 of Lecture Notes in Physics, Berlin Springer Verlag, Supernova Interaction with a Circumstellar Medium. pp 171–194
- Chevalier R. A., Fransson C., Nymark T. K., 2006, ApJ, 641, 1029
- Chevalier R. A., Irwin C. M., 2012, ApJL, 747, L17
- de Jager C., Nieuwenhuijzen H., van der Hucht K. A., 1988, A&AS, 72, 259
- Dickey J. M., Lockman F. J., 1990, ARAA, 28, 215
- Dwarkadas V. V., 2011, MNRAS, 412, 1639
- Dwarkadas V. V., Dewey D., Bauer F., 2010, MNRAS, 407, 812
- Dwarkadas V. V., Gruszko J., 2012, MNRAS, 419, 1515
- Fransson C., 1982, AA, 111, 140
- Fransson C., Lundqvist P., Chevalier R. A., 1996, ApJ, 461, 993
- Georgy C., Ekström S., Meynet G., Massey P., Levesque E. M., Hirschi R., Eggenberger P., Maeder A., 2012, AA, 542, A29
- Georgy C., Ekström S., Saio H., Meynet G., Groh J., Granada A., 2013, in Kervella P., Le Bertre T., Perrin G., eds, EAS Publications Series Vol. 60 of EAS Publications Series, How the mass-loss rates of red-supergiants determine the fate of massive stars?. pp 43–50
- Groh J. H., Meynet G., Georgy C., Ekstrom S., 2013, ArXiv e-prints
- Humphreys R. M., 2007, in Revista Mexicana de Astronomia y Astrofisica Conference Series Vol. 30 of Revista Mexicana de Astronomia y Astrofisica, vol. 27, The Circumstellar Environments of the Cool Hypergiants: Implications for the Mass Loss Mechanism. pp 6–11
- Insera C., Turatto M., Pastorello A., Benetti S., Cappellaro E., Pumo M. L., Zampieri L., Agnoletto I., Bufano F., Botticella M. T., 2011, MNRAS, 417, 261

- Inserra C., Turatto M., Pastorello A., Pumo M. L., Baron E., Benetti S., Cappellaro E., Taubenberger S., Bufano F., Elias-Rosa N., 2012, MNRAS, 422, 1122
- Jerkstrand A., Fransson C., Maguire K., Smartt S., Ergon M., Spyromilio J., 2012, AA, 546, A28
- Josselin E., Blommaert J. A. D. L., Groenewegen M. A. T., Omont A., Li F. L., 2000, AA, 357, 225
- Jura M., 1986, ApJ, 303, 327
- Kalberla P. M. W., Burton W. B., Hartmann D., Arnal E. M., Bajaja E., Morras R., Pöppel W. G. L., 2005, AA, 440, 775
- Kallman T. R., McCray R., 1982, ApJS, 50, 263
- Kelly P. L., Kirshner R. P., 2012, ApJ, 759, 107
- Knapp G. R., Morris M., 1985, ApJ, 292, 640
- Langer N., 1993, Space Science Reviews, 66, 365
- Langer N., 2012, ARAA, 50, 107
- Lundqvist P., Fransson C., 1996, ApJ, 464, 924
- Maeder A., Meynet G., 2000, ARAA, 38, 143
- Maund J. R., Fraser M., Smartt S. J., Botticella M. T., Barbarino C., Childress M., Gal-Yam A., Inserra C., Pignata G., Reichart D., Schmidt B., Sollerman J., Taddia F., Tomasella L., Valenti S., Yaron O., 2013, MNRAS, 431, L102
- Maund J. R., Mattila S., Ramirez-Ruiz E., Eldridge J. J., 2014, MNRAS
- Maund J. R., Reilly E., Mattila S., 2014, MNRAS
- Mauron N., Josselin E., 2011, AA, 526, A156
- Misra K., Pooley D., Chandra P., Bhattacharya D., Ray A. K., Sagar R., Lewin W. H. G., 2007, MNRAS, 381, 280
- Moriya T., Tominaga N., Blinnikov S. I., Baklanov P. V., Sorokina E. I., 2011, MNRAS, 415, 199
- Moriya T. J., Tominaga N., Blinnikov S. I., Baklanov P. V., Sorokina E. I., 2012, in Death of Massive Stars: Supernovae and Gamma-Ray Bursts Vol. 279 of IAU Symposium, Ultraviolet-Bright Type IIP Supernovae from Massive Red Supergiants. pp 54–57
- Nieuwenhuijzen H., de Jager C., 1990, AA, 231, 134
- Pan T., Patnaude D., Loeb A., 2013, MNRAS, 433, 838
- Piro A. L., Ott C. D., 2011, ApJ, 736, 108
- Reimers D., 1975, Memoires of the Societe Royale des Sciences de Liege, 8, 369
- Roy R., Kumar B., Benetti S., Pastorello A., Yuan F., Brown P. J., Immler S., Fatkhullin T. A., Moskvitin A. S., Maund J., Akerlof C. W., Wheeler J. C., Sokolov V. V. e. a., 2011, ApJ, 736, 76
- Salasnich B., Bressan A., Chiosi C., 1999, AA, 342, 131
- Schaller G., Schaerer D., Meynet G., Maeder A., 1992, AApS, 96, 269
- Smartt S. J., 2009, ARAA, 47, 63
- Smartt S. J., Eldridge J. J., Crockett R. M., Maund J. R., 2009, MNRAS, 395, 1409
- Sollerman J., Cumming R. J., Lundqvist P., 1998, ApJ, 493, 933
- Taddia F., Stritzinger M. D., Sollerman J., Phillips M. M., Anderson J. P., Boldt L., Campillay A., Castellón S. e. a., 2013, AA, 555, A10
- Tomasella L., Cappellaro E., Fraser M., Pumo M. L., Pastorello A., Pignata G., Benetti S., Bufano F., Dennefeld M., Harutyunyan A., Iijima T., Jerkstrand A., Kankare E., Kotak R. e. a., 2013, MNRAS
- Tsvetkov D. Y., 1995, Information Bulletin on Variable Stars, 4253, 1
- Utrobin V. P., Chugai N. N., 2008, AA, 491, 507
- Utrobin V. P., Chugai N. N., 2009, AA, 506, 829
- Utrobin V. P., Chugai N. N., 2011, AA, 532, A100
- Utrobin V. P., Chugai N. N., 2013, AA, 555, A145
- Utrobin V. P., Chugai N. N., Botticella M. T., 2010, ApJL, 723, L89
- Utrobin V. P., Chugai N. N., Pastorello A., 2007, AA, 475, 973
- Van Dyk S. D., Cenko S. B., Poznanski D., Arcavi I., Gal-Yam A., Filippenko A. V., Silverio K., Stockton A., Cuillandre J.-C., Marcy G. W., Howard A. W., Isaacson H., 2012, ApJ, 756, 131
- Van Dyk S. D., Davidge T. J., Elias-Rosa N., Taubenberger S., Li W., Levesque E. M., Howerton S., Pignata G., Morrell N., Hamuy M., Filippenko A. V., 2012, AJ, 143, 19
- van Loon J. T., Cioni M.-R. L., Zijlstra A. A., Loup C., 2005, AA, 438, 273
- Vanbeveren D., De Loore C., Van Rensbergen W., 1998, A&ARevs, 9, 63

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